Climate Compatible Growth
UKaid from the British people
CHATHAM HOUSE
Foreign, Commonwealth & Development Office

The geopolitics of critical materials and minerals and implications for the low-carbon transition

Karla Cervantes Barron*[1], Shobhan Dhir[2], and Jonathan M Cullen[3]

Summary

The transition to low-carbon energy requires radical infrastructure changes and an expansion in the use of low-carbon technologies. The expansion of these systems also comes with increasing complexity in the materials used to make them, with more and more specialised materials being needed.

This brief examines the critical materials cobalt, copper, graphite, lithium, nickel and rare earth elements (REEs). The material supply risks and geopolitical concerns are assessed and strategies to address them are proposed.

Key Policy Recommendations

- Country strategies must aim to improve the resilience against supply disruptions and diversify mineral supplies.
- Mineral producing country strategies include providing financial and investment support to strategically important projects, improving the efficiency of permitting procedures for new projects, and establishing high Environmental, Social and Governance (ESG) standards.
- Mineral consuming country strategies include supporting the development of a recycling and waste recovery industry, strategic stockpiling of critical minerals, and developing strategic relationships with producers.
- Strong relationships between producers and consumers and strategic policy co-ordination are the most important strategies to ensure reliable and secure global supplies of critical minerals.
- Updating and funding national geological surveys is critical in developing and emerging economies to attract investment and develop domestic production.

Key geopolitical concerns

The main concern for critical minerals is that their supply and processing is geographically concentrated. This concentration creates dependencies and vulnerability to supply shocks, sudden policy shifts and geopolitical events. Lithium is one of the minerals of greatest concern with the highest demand growth and lack of current substitutes. Copper is a mineral used in almost all clean energy technologies, and it faces significant pressures from declining ore quality. Russia is the world's top supplier of battery-grade nickel, providing significant uncertainty for future nickel supply. Cobalt relies on the Democratic Republic of Congo for 70% of supply, whose production has a high ESG risk.

However, the main critical mineral stakeholder is China, while the rest of the producers have been too slow to catch up. China dominates the processing of most critical minerals needed in low-carbon transition technologies, processing over half of all lithium, cobalt and graphite and 90% of REEs. It is also the largest processor of both copper and nickel. This dominance is increasing particularly for battery metals where China has the greatest share of announced additional processing capacity to 2030. China dominates the REE and graphite supply chain end-to-end, and its companies are significantly involved in both nickel and cobalt mining. This global reliance on a single country for the majority of critical minerals processing leads to significant vulnerability for supply of global critical minerals to geopolitical events and supply shocks, thus increasing the risks of hindering the progress of low-carbon transitions.

Introduction

The transition to low-carbon energy requires radical infrastructure changes and an expansion in the use of low-carbon technologies. The infrastructure and technologies needed include low-carbon electricity generation plants, electricity storage, electric vehicles, heat pumps, and batteries, among others. The expansion of these systems comes with increasing amounts and complexity of the materials used to make them. Material processing and low-carbon technology production is geographically focused. Thus, increasing supply security as the low-carbon transition occurs is essential.

This brief highlights the critical mineral and material demand for low-carbon systems, their geographical provision and the geopolitical implications of their supply chains. Strategies to address supply risks given such geopolitical implications are proposed.

The methodology behind this brief includes a review of relevant literature, and an analysis of data and scenarios from the International Energy Agency (IEA) and other sources. The scenarios used are the Stated Policies and Sustainable Development scenarios from the IEA. The fist scenario refers to policies and measures that exist and are under development, while the second assumes an evolution of the energy sector which reaches key energy-related goals, and complies with the Paris Agreement limiting global temperature rise to below 1.8°C [1].

Which materials and minerals are critical for the low-carbon transition?

Material criticality usually refers to the relationship between supply disruption probability and the vulnerability to such disruption. Supply disruption probability is an assessment of material supply chains, while the vulnerability in this instance includes geopolitical or socioeconomic aspects. Criticality also refers to the small amounts of material needed, but which are essential for the functioning of a component or device.

Some countries or regions create their own lists of critical materials, which tend to be revised every few years. The latest additions to the US and European Union's (EU) lists in 2022 include more battery materials and rare earth elements [2], [3]. This highlights the effect that the transition is having on security of supply concerns.

Critical materials and minerals in low-carbon energy systems include cobalt, copper, graphite, lithium, nickel, rare earth elements (REEs), manganese, molybdenum, graphite, chromium, platinum group metals, and zinc, among others. This brief will cover the first six of these in detail and only discuss the others more broadly, given the demand or concentrated supply chains for the former.

Future critical material demand

Demand for critical materials is expected to increase as low-carbon systems are deployed.

Figure 1 shows the critical material demand for selected materials by 2040 and for two different scenarios. Copper has the highest demand, followed by nickel and graphite.

Figure 2 shows the share of the material demand required for specific applications in 2030. Electric vehicles (EVs) require the highest share of most minerals (53-97%) apart from copper. Copper is mostly needed for electricity networks (78%). Wind turbines also have an important share of REEs (43%). Given the expansion of EVs by 2040, their mineral demand grows, yet the expansion of battery storage increases its share of graphite, lithium and cobalt, requiring 15%, 10% and 6% of each respectively.

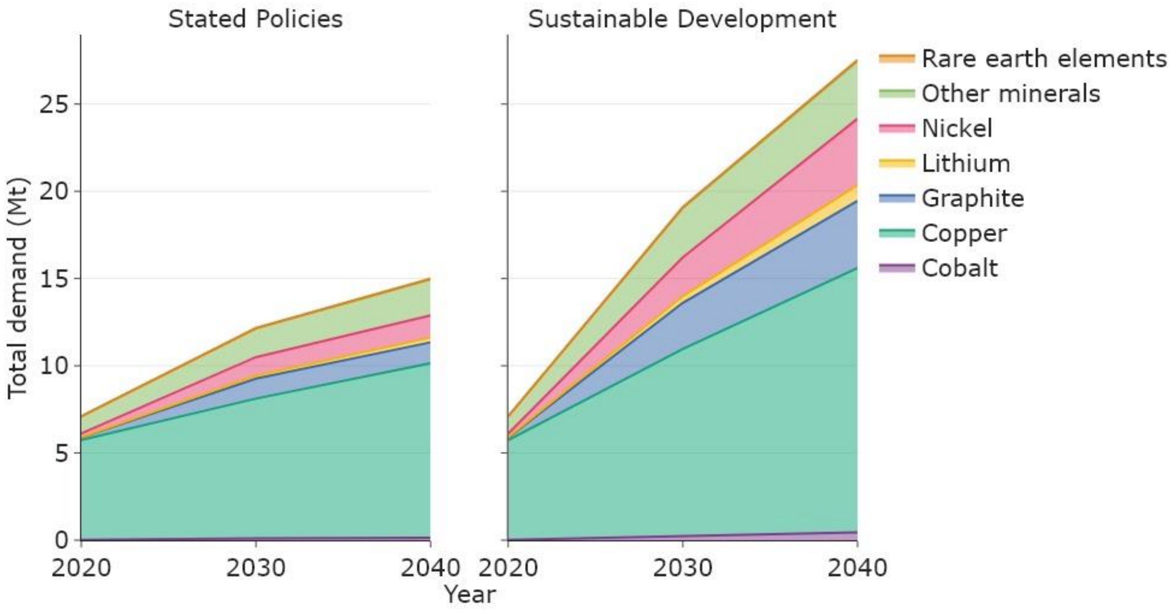

Figure 1 Critical material demand for Stated Policies and Sustainable Development Scenarios from the IEA. Data source: [4]

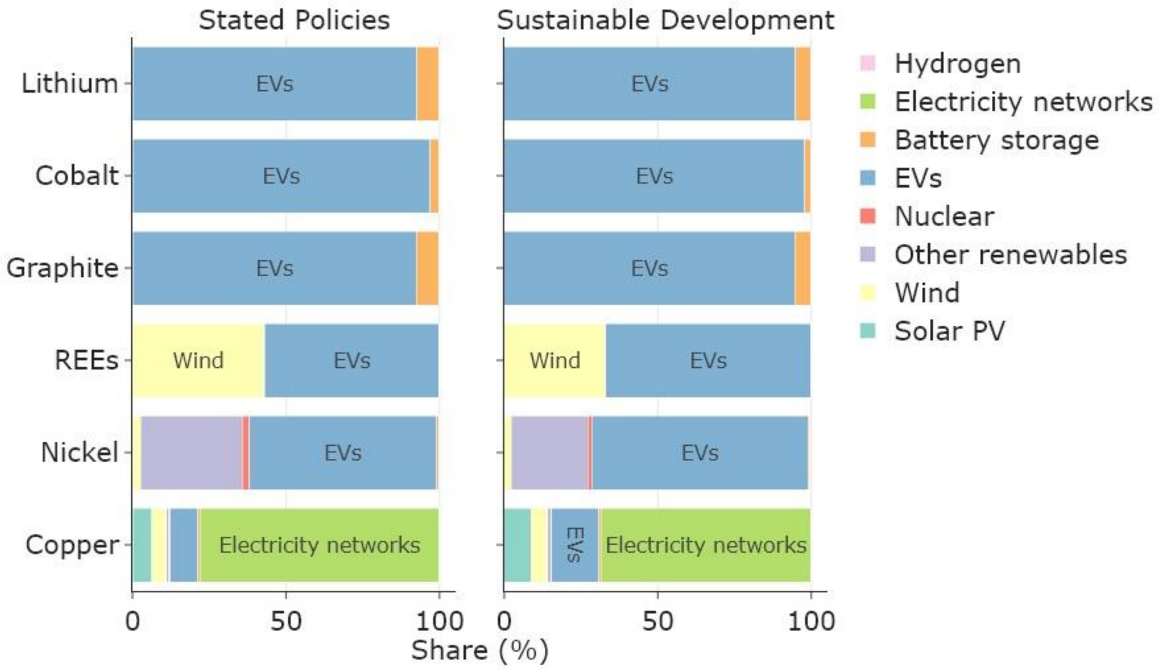

Figure 2 Share of material demand by sector in 2030 for the Stated Policies and Sustainable Development Scenarios from the IEA. Data source: [4]. Solar PV refers to solar photovoltaic, while EVs refers to electric vehicles.

Geopolitics of critical material supply

Currently the extraction and processing of critical minerals are geographically concentrated. **Figure 3** shows the country shares of reserves, extraction and processing of critical minerals. China dominates critical mineral mining and processing, despite it only having the largest reserves of REEs but not of other materials (among those materials included in this brief). China is the leader in both extraction of REE (61%) and graphite (79%), and in processing of all the materials presented (from 35-87% depending on the material). The Democratic Republic of Congo (DRC) is the leader in cobalt extraction (73%). Australia, Chile and China are the top three lithium extraction players, yet the largest reserves are in Chile (42%) and Australia (26%). The highest extraction of nickel and copper is by Indonesia (36%) and Chile (27%) respectively. However, nickel and copper extraction is less geographically concentrated than other materials and has even less concentrated reserves.

Beyond extraction and processing, low-carbon technology manufacturing is more diverse but also somewhat concentrated. China dominates manufacturing of batteries, solar panels, and blades and nacelles for wind [5]. Six Chinese companies hold two-thirds of global production capacity for battery anodes [6].

> ***“China dominates critical mineral processing, despite it only having the largest reserves of REEs.”***

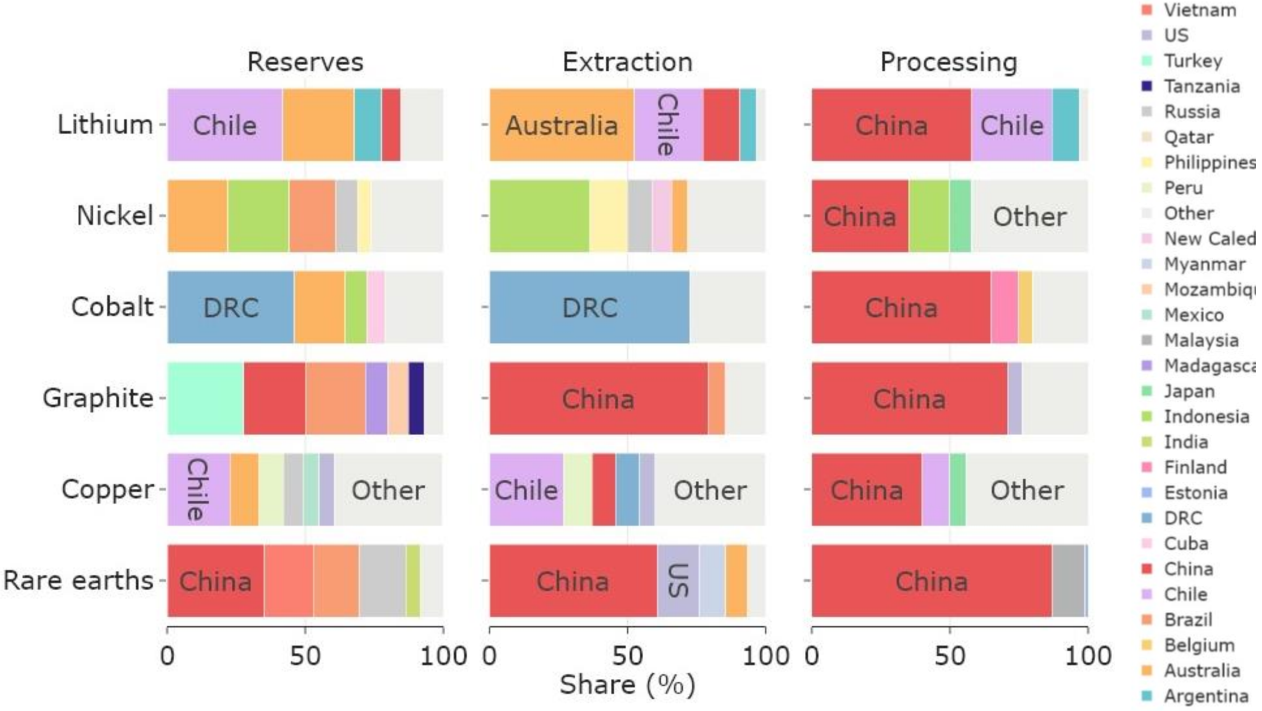

Figure 3 Share of total reserves, extraction and processing of critical materials in 2021 (reserves and extraction) and 2019 (processing) respectively. Data sources: [7] [4]. No data on graphite processing is available.

Details regarding the production of each material, their supply concerns and the geopolitical implications are presented by each material below:

Lithium

Lithium is one of the minerals of greatest concern regarding supply security and faces supply challenges in the short, medium and long-term. Large-scale deployment of EVs is critical to decarbonising the road transport sector and reaching net zero emissions. Batteries are by far the leading decarbonisation solution for light duty vehicles (LDVs) and currently lithium-ion (Li-ion) batteries are the only commercial battery chemistry available at scale that provide viable EV performance. Batteries are the primary source of lithium demand [8].

Supply risks

Lithium is the only element of the cathode and anode materials which is irreplaceable for Li-ion batteries. **Currently, there are no substitutes for lithium and this is one of the largest risks to transport decarbonisation**. Sodium-ion (Na-ion) is the leading substitution chemistry which is now being developed by several companies including the world's largest battery maker CATL. However, Na-ion electrode material supply chains must be developed and scalability demonstrated, and its impact by 2030 is likely to be small.

Lithium prices have experienced unprecedented price volatility recently, increasing more than sevenfold since the start of 2021 [8], and falling significantly in the last few months. The exceptional price rises have been due to a combination of the surging demand for Li-ion batteries, supply chain challenges such as from the pandemic and Russia's invasion of Ukraine, and critically from underinvestment in new production in the years of low prices proceeding 2021. This has already had significant impact on battery prices. **2022 was the first year that battery pack prices increased**, up 7% from 2021 [9], reversing a decade of battery pack cost declines and posing significant challenge to the EV industry. Higher battery prices delay cost competitiveness with ICEs hence slowing EV uptake. High Li prices have stimulated investment in new Li supply however the price volatility also undermines confidence for investors, providing greater uncertainty.

The greater issue is medium and long term. **Lithium faces the greatest demand growth of all critical minerals** driven by the rapid growth in EV demand. Demand increase is estimated to increase over 100-times from 2020 to 2050 [10]. **Lithium also appears to face the largest supply gap of the critical minerals by 2030** [5] [8]. The significant lead times for new mines poses risks of supply shortages, price volatility and price rises for batteries, and slowing EV uptake [5] [8].

Li-ion battery recycling is still in its infancy, with the current lithium recycling rate being <1% [4]. In the long-term, this will be a substantial source of lithium supply. However, before 2030 secondary lithium supply will be minimal given the small volume of retired EVs [6].

Geopolitical concerns

Lithium supply is geographically concentrated. **Over half of extraction is from Australia and over half of global processing is in China**. This creates dependencies, and vulnerabilities to supply shocks and geopolitical challenges. Currently, Australia refines little of the lithium ore it produces and ships it to China for processing. Recent tensions between the countries could be a concern going forward for lithium supply. Australia is trying to develop domestic processing capability though this will take considerable time. China will retain its dominance of processing in the medium-term, having the greatest share of announced additional lithium processing capacity to 2030 (60%) [5].

Finally, one of the most critical aspects affecting lithium supply is its environmental impact. Over half of all lithium production is located in areas with high water stress levels [4]. **Environmental and social impact concerns are having ramifications on the social licenses to operate and new projects developments**. Recent examples include the cancellation of the Jadar project in Serbia [11], Chilean protests against lithium extraction contracts [12], or the pushback to the US Thacker Pass lithium mine [13], the largest lithium deposit in the US, which despite having all necessary permits awaits a ruling on its continuation due to community resistance over its environmental impact. Thus, unless Environmental, Social and Governance (ESG) risks are managed properly, there can be major disruptions to future lithium supply and significant delays to the low carbon transition.

Co

Cobalt

Cobalt is critical for both portable electronics and the current leading long range EV cathode chemistries, and batteries are the main cobalt demand source. Cobalt content has been progressively decreasing in EV battery cathodes in favour of higher nickel content for higher energy density. However, cobalt-free high energy density cathode chemistries such as lithium nickel oxide (LNO) or lithium-manganese-rich nickel-manganese-cobalt oxide (LMR-NMC) still have research challenges to solve. Despite the decreasing cathode cobalt content, cobalt demand is set to grow 6-22 times by 2040 depending on the scenario (see Figure 1). Cobalt is primarily mined as a by-product of copper or nickel mining.

Supply risks and geopolitical concerns

The primary supply risk for cobalt is the geographical concentration of its production and processing. **The DRC mines 73% of global cobalt supply while China processes 65%**. Dependency on the DRC comes with significant risk. Being reliant on a single source presents greater risks to supply shocks and challenges in any country, however, the DRC is considered to have high political instability risks [4]. Cobalt mining in the DRC has also been associated with human rights abuses and child labour [14]. Cobalt is often considered one of the highest ESG risk critical minerals [15] and has been identified as the most at risk critical mineral due these factors [16]. Thus, the DRC has a higher risk of supply shocks, which could disrupt global supply. Companies also face reputation risk if associated with exploitative cobalt mining. This may result in investor- or consumer-led consequences such as divestment or product boycotting.

Despite the DRC being the top producing country, **several of the largest cobalt mining companies are Chinese**. Glencore is the current largest cobalt producer however, the Chinese company CMOC (previously China Molybdenum) has announced major investments and expansion plans for cobalt mining in the DRC [17], and it has expressed intent to be the top producer in the next few years [18].

Recently, there has been a major dispute between the Chinese company CMOC and the DRC state mining company Gecamines, leading to exports from the world's second largest cobalt mine being blocked [19]. If this dispute is not solved quickly between the top producer and top processor, or the relationship between the two countries deteriorates, there could be substantial disruption of global cobalt supply.

Nevertheless, unlike lithium, **cobalt supply concerns can be somewhat mitigated by substitution and recycling**. Lithium iron phosphate (LFP) cathodes contain no cobalt or nickel. They are lower energy density than nickel-rich chemistries. However, the recent cell-to-pack (CTP) technology innovation has improved LFP energy density, making them more competitive. LFP saw a major recent resurgence, doubling its share in EVs between 2020 and 2021 [8] as battery makers try to reduce exposure to commodity price rises. Almost half of all Tesla EVs made in the first quarter of 2022 were LFP [8]. LFP provides a critical solution to mitigate supply challenges from future major cobalt supply issues.

Cobalt is the most expensive metal in Li-ion batteries. Therefore, it has one of the best economic cases for recycling and in the long-term recycling will be a significant source of supply. Currently the recycling rate is high at around 30% [4]. Though again, like lithium, any impact from battery recycling by 2030 will be minimal [6].

Cu

Copper

Copper is a critical mineral required for almost all clean energy technologies electricity networks, solar PV, batteries and wind turbines. Copper is ideal for electrical wiring because it is easily worked, can be drawn into fine wire and has a high electrical conductivity.

Copper supply security concerns are for the medium- and long-term. **A shortfall is anticipated from 2025 to meet Net Zero goals by 2050** [20]. Substitution and recycling will not be enough to meet the demands. Even in a scenario with highly optimistic mine and processing capacity utilisation and recycling rate assumptions, shortfalls are shown in 2035 [20]. China accounts for 80% of the announced increase in mining and processing capacity for copper by 2030 [5] .

One of the **main challenges in copper supply is the declining copper ore quality**. Average concentrate grades in Chile decreased by 30% since 2005 [4], leading to increased costs of extraction, greater emissions, and waste. Like lithium, over half of copper supply is in areas of high water stress levels also providing significant ESG risk [4].

Copper can be substituted by aluminium in some applications, however aluminium is more carbon intensive to produce than copper. Some types of copper electricity lines can be replaced, but would require greater maintenance and thicker cables (due to aluminium's lower conductivity, and inferior mechanical and thermal properties). Applications where no substitutions are possible include anode current collector of Li-ion batteries (since lithium alloys with aluminium at low potentials), and subsea and underground electricity lines.

Copper reserves are available for extraction, yet mine lead times are high since some projects face either economic or permitting challenges. Projects currently under development are unlikely to offset projected shortfalls in copper supply, even with accelerated permitting and construction [20].

Copper recycling is well established; the end-of-life recycling rate is around 45% [4]. Despite this, copper recycling must increase to help avoid future shortfalls [20].

Ni

Nickel

Nickel is critical for stainless steel production (the largest source of demand); however, EV batteries are the fastest-growing source of nickel demand. The leading high energy density battery cathode chemistries for EVs are nickel-rich (around 80% of LDV EV sales share in 2021) [8]. However, batteries require Class 1 (>99.8%) high purity nickel, unlike steel which only needs Class 2 nickel (<99.8%). There are concerns for nickel supply in both the short- and long-term.

Supply risks and geopolitical concerns

Russia is the world's top supplier for Class 1 battery-grade nickel which is a high risk for nickel supply. Currently nickel is not affected by sanctions on Russia [21], however, there is uncertainty as the war continues. The London Metal Exchange (LME) has recently rejected a call for a ban on Russian nickel from producers, traders and consumers, believing unwanted Russian nickel flooding into LME warehouses would disrupt the market. Some consumers are self-sanctioning, refusing to buy Russian nickel, or have fears of market price distortions. LME may impose future restrictions, generating market uncertainty [22].

The leading nickel-rich Li-ion battery NMC811 (which has almost seven times more nickel than lithium by mass) prices are sensitive to nickel price movement. **Nickel experienced unprecedented price volatility in 2022, causing LME to shut down its trading**. That volatility was primarily due to a short squeeze [23] with contributions from concerns about supply of Russian Class 1 nickel. The price fluctuations have undermined confidence in the market, affecting investment prospects in new supply needed for future demand.

Indonesia is the current top extractor of nickel, however, its ore is low-grade producing Class 2 nickel. Novel techniques to produce Class 1 nickel from low-grade sources are making progress. Yet, Indonesia has banned ore exports from 2020, disrupting trade flows and supply. The ban aimed to develop the domestic processing industry [24], and it was followed by bauxite (aluminium ore) export bans [25]. Export bans, such as that of Indonesia on nickel, can be effective for developing domestic processing capacity, but can disrupt global supply. The DRC attempted a similar ban however, has not had the same success as Indonesia. This emphasises the vulnerability of highly geographically concentrated supply and the need for diversified supply.

Nickel has one of the largest supply gaps in 2030 for both mining and processing [5]. This demonstrates risk of future supply shortages and price volatility without investment in new mines now, given the long lead times (often above 10 years) to get new mines operational [4]. Therefore, current price volatility and market uncertainty affects future nickel supply.

Nickel can be substituted by changing cathode chemistries from nickel-rich ones to LFP (containing no nickel). Though LFP energy density is increasing with the CTP innovation, it still cannot challenge the high energy densities of high nickel chemistries. Therefore, nickel shortages and supply concerns will restrict the ability to sell long-range EVs. This would hinder EV uptake in US and European markets where longer range is important to consumers. Nickel recycling is more developed than other battery metals with a current 60% end-of-life recycling rate [4]. With EV batteries being such a significant source of growing nickel demand, recycled nickel will be an important potential supply source after 2030 when larger volumes of EVs retire [4].

REEs

Rare earth elements

REEs refer to 17 elements including 15 lanthanides group plus scandium and yttrium. REEs are classified as light (LREE, first 6 in the lanthanides group) and heavy (HREE, the rest of the lanthanides group).

Neodymium (Nd), dysprosium and praseodymium are used in permanent magnets for motors in EVs and wind turbines. Nd is also used in catalytic converters.

REE ores contain several elements, with composition varying by deposit. The elements are separated from the concentrate using acids at high temperatures. Radioactive elements, namely uranium and thorium, can be found in the ores and are also separated in the process.

Supply risks and geopolitical concerns

China dominates the REE supply chain end-to-end, with almost 61% market share in REE mining and 90% across the supply chain, from processing to magnet making [4]. China dominates HREE production, while four facilities exist for LREE in Malaysia, France, India and Estonia. Thus, supply disruptions – given China's dominance – are the greatest concern. Previously China banned the export of REEs to give preference to domestic firms in 2010 in a major disruption to global supply, sending prices soaring. This demonstrates the risks of sudden policy shifts with such high concentration of supply [4].

Mining capacity is expanding, albeit slowly, in Australia [26], North America, Africa and Europe [27] [28]. Sweden's LKAB company announced a discovery of Europe's largest deposit of REEs with more than one million tonnes of rare earth oxides, and estimated it would take 10 to 15 years before the raw materials could be delivered to market [29]. Japan also announced it will extract rare earths from its seabed by 2024 [30].

Another challenge is that REEs are produced together; therefore, price differences between the different REEs can complicate and affect profits from extraction.

REE material substitution for magnets or reduced quantities in applications is being explored with significant progress made to reduce dependency on China [28]. Hitachi metals is exploring the substitution of neodymium by ferrite in motor magnets [31]. BMW's new electric motor is magnet free [32]. REE recycling is in its infancy with <1% current recycling rate [4]. Recycling challenges include the fact such small quantities are used, making REEs often too expensive to recover.

Si Mn Gr

Other (Silicon, Manganese, Graphite)

Other materials such as silicon, manganese and graphite are used in EV batteries, solar cells and semiconductors. Graphite demand growth is driven by EV battery anodes, with EV batteries using 25% of all processed graphite [33]. Of this, synthetic dominates over natural graphite, yet competition is growing depending on availability and prices [34]. Synthetic graphite costs depend on energy costs, given the high energy requirements [34]. Silicon is used in aluminium alloys (45%), silicones and silanes (35%), solar cells (12%) and semiconductors (3%) [33]. In the energy transition, silicon for solar cells and battery applications are important. Silicon is used in silicon-based anodes as an addition to graphite in EVs to increase energy density and reduce charging time [28]. Manganese is used in the cathode of EV batteries such as leading NMC cathodes.

Graphite is abundant, but producing battery-grade graphite is complex due to material quality and know-how required. The knowledge gap is being addressed by US manufacturers. The share of graphite in EV battery anode material will decrease post 2030, due to increasing use of silicon and lithium metal anodes. Yet, EV demand growth and applications such as steelmaking applications will increase graphite demand. **China dominates the entire graphite supply chain end-to-end**.

The leading silicon producer is China (71%), followed somewhat by Russia (7%) [7]. Silicon supply has no expected shortages. On the contrary, increasing Chinese silicon production may cause price drops [35], disrupting supplier competition.

Manganese production in 2021 was dominated by South Africa (37%). Gabon (18%), Australia (17%), and China (7%) [7] are also important producers. The rest of the production is widely distributed.

Geopolitical concerns

Graphite and silicon production is highly concentrated in China. Supply dependence from China creates risks of supply shocks. Advanced graphite projects exist in several African countries, North America and Australia [36] which could reduce competition for resources with China. The US has partnered with Mozambique's Syrah mining company, which will sell mined graphite to a US anode producer [37]. Supply and ESG risks exist in natural graphite production in Mozambique and China (due to strikes and production slowdown respectively) [34], and for environmental degradation in graphite production.

Overcoming the challenges: Strategies for critical material security of supply

The type of strategies to pursue to increase critical material supply security can be split by material producing and consuming countries, yet some partnership and collaboration strategies are critical to both. **Table 1** presents a summary of proposed material strategies for different types of countries.

Table 1 Government strategies for critical mineral security based on country conditions.

Critical mineral extracting/ processing countries	**Material mining and production** • Funding updated national geological surveys and pre-commercial resource mapping. • Preserve extraction value by doing more in-house processing. • Provide grants for early- to mid-stage projects so they survive the pre-profit stage. • Increase efficiency of permitting and regulation procedures to reduce lead times. • Provide government financial support or public investment to critical projects to de-risk strategically-important projects. • Raise awareness of economic and climate advantages of projects with local communities. • Establish and maintain high ESG standards.
Critical mineral consuming countries	**Securing material supply** • Conduct national-level government procurement. • Stockpile strategic materials responsibly. • Create strategic partnerships with producers. • Diversify supply by investing in substitution and efficiency Research and Development (R&D). • Develop and incentivise investment in domestic processing capacity, if feasible, thereby ensuring availability of know-how. **Material mining and production** • Incentivise material efficiency. • Provide financial support for recycling and waste recovery technologies/projects. • Support and incentivise recycling collection and sorting. **Risk mitigation** • Establish a risk assessment framework. • Create emergency response strategies and exercises, as well as stress tests. • Conduct supply chain due diligence. • Regulate responsible sourcing.
Supporting activities for all	• Co-ordinate policy security efforts with other countries. • Develop strategic partnerships and participate in international coordination initiatives. • Formalise knowledge sharing practices to achieve ESG goals while securing supply.

Overall, country strategies must aim **to improve resilience against supply disruptions and diversify mineral supplies.** Critical policy strategies for **producer** countries include providing **financial and investment support to strategically important projects, improving the efficiency of permitting procedures for new projects, and establishing high ESG standards**. For instance, the 2021 US Infrastructure Investment and Jobs Act (IIJA) aims to improve the efficiency of permitting for critical minerals mines by establishing and adhering to set schedules [38].

Funding updated geological surveys is of critical importance for developing and emerging economies to attract investment and develop domestic production where resource surveys were often conducted a long time ago. As well as being out of date, battery critical minerals were not given attention at that time. For example, the US Geological Survey shows limited nickel reserve numbers for the East African Nickel Belt, however mining company BHP invested $100m in 2021 in a Tanzanian nickel project, citing one of the largest nickel sulphide deposits [39] [7].

The 2022 US Inflation Reduction Act (IRA) is an example of critical mineral policy strategies to increase domestic production [40]. The IRA will provide tax breaks for critical mineral mining companies, and requires at least 40% of domestic or Free Trade Agreement Partner sourcing of critical minerals in EV batteries. Despite the ambitious IRA plans, legislation to increase material substitution is lacking [41]. Other existing producer initiatives are expanding technical assistance between countries [42] [43].

Important strategies for **consumer** countries include **supporting the development of a recycling and waste recovery industry, strategic stockpiling of critical minerals, and developing strategic relationships with producers**. Regional strategies such as the EU's proposal to create a Critical Raw Materials Act (CRMA) [44] are being set up. The CRMA seeks to create strategies for critical material innovation and substitution, enhancing supply security, and addressing material production environmental and social concerns. Bilateral and other partnerships are being established to increase security of supply for consumers, for example between Canada and the EU [45].

Joint country strategies to increase security of supply is to co-ordinate policy security efforts. Strong relationships between producers and consumers and strategic policy co-ordination are the most important strategies to ensure reliable and secure global supplies of critical minerals. Existing partnerships aim to expand primary and secondary material supply, bringing economic benefits, and adhering to ESG standards, for example the Minerals Security Partnership [46].

References

[1] IEA, 'World Energy Model Documentation', *World Energy Outlook*, 2020. https://www.iea.org/reports/world-energy-model/documentation#abstract (accessed Dec. 02, 2020).

[2] European Commission, 'Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability'. European Commission, Brussels, 2022. [Online]. Available: http://info.worldbank.org/governance/wgi/.

[3] United States Geological Survey, 'United States Geological Survey releases 2022 list of critical minerals', *2022 list of critical minerals*, 2022. https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals (accessed Jan. 13, 2023).

[4] International Energy Agency, 'The Role of Critical Minerals in Clean Energy Transitions', International Energy Agency, France, 2021. Accessed: Jan. 10, 2023. [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[5] IEA, 'Energy Technology Perspectives 2023', 2023.

[6] IEA, 'Global Supply Chains of EV Batteries'. Accessed: Jan. 17, 2023. [Online]. Available: https://www.iea.org/reports/global-supply-chains-of-ev-batteries

[7] National Minerals Information Center, 'U.S. Geological Survey Mineral Commodity Summaries 2022 Data Release'. U.S. Geological Survey, 2022. doi: 10.5066/P9KKMCP4.

[8] IEA, 'Global EV Outlook 2022'. Accessed: Jan. 16, 2023. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2022

[9] Bloomberg NEF, 'Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh', *BloombergNEF*, Dec. 06, 2022. https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/ (accessed Jan. 16, 2023).

[10] International Energy Agency, 'World Energy Outlook 2022', International Energy Agency, 2022.

[11] I. Sekularac, 'Serbia revokes Rio Tinto lithium project licences amid protests', *Reuters*, Jan. 20, 2022. Accessed: Jan. 16, 2023. [Online]. Available: https://www.reuters.com/business/retail-consumer/serbian-government-revokes-rio-tintos-licences-lithium-project-2022-01-20/

[12] Agence France-Presse, 'Chileans protest lithium contract sale', *France 24*, Jan. 08, 2022. https://www.france24.com/en/live-news/20220108-chileans-protest-lithium-contract-sale (accessed Jan. 16, 2023).

[13] E. Scheyder and E. Scheyder, 'Ruling in Thacker Pass lithium mine case expected within months', *Reuters*, Jan. 05, 2023. Accessed: Jan. 16, 2023. [Online]. Available: https://www.reuters.com/legal/us-judge-rule-thacker-pass-lithium-mine-case-within-months-2023-01-05/

[14] Amnesty International, 'Democratic Republic of Congo: "This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt'. Accessed: Jan. 16, 2023. [Online]. Available: https://www.amnesty.org/en/documents/afr62/3183/2016/en/

[15] International Energy Agency, 'Securing Clean Energy Technology Supply Chains', OECD, Aug. 2022. doi: 10.1787/be931bdc-en.

[16] Project Blue, 'Project Blue: Cobalt the most at risk critical material of 2022', May 09, 2022. https://www.prnewswire.co.uk/news-releases/project-blue-cobalt-the-most-at-risk-critical-material-of-2022-880831389.html (accessed Jan. 16, 2023).

[17] Green Car Congress, 'CMOC to invest $2.5B to expand copper and cobalt output at TFM mine in DRC', *Green Car Congress*, 16 2021. https://www.greencarcongress.com/2021/08/20210816-cmoc.html (accessed Jan. 16, 2023).

[18] S. Watanabe, 'Chinese cobalt producer to double Congo output with eye on top spot', *Nikkei Asia*, 2022.

[19] S. Rolley and H. Reid, 'CMOC threatens legal action over Congo cobalt mine export block', *MINING.COM*, Dec. 05, 2022. Accessed: Jan. 16, 2023. [Online]. Available: https://www.mining.com/web/cmoc-threatens-legal-action-over-congo-cobalt-mine-export-block/

[20] S&P Global, 'The future of Copper in the Energy Transition', S&P Global. Accessed:

Jan. 15, 2023. [Online]. Available: https://cdn.ihsmarkit.com/www/pdf/1022/The-Future-of-Copper_Full-Report_SPGlobal.pdf

[21] H. Dempsey and L. Hook, ‘LME’s Russian metal dilemma threatens market turmoil’, *Financial Times*, Oct. 20, 2022. Accessed: Jan. 17, 2023. [Online]. Available: https://www.ft.com/content/e38371fc-8163-433c-8da4-260b0e9a5937

[22] H. Dempsey and L. Hook, ‘London Metal Exchange rejects calls to ban Russian metal’, *Financial Times*, Nov. 11, 2022. Accessed: Jan. 16, 2023. [Online]. Available: https://www.ft.com/content/e9b2a837-2160-43cc-a4b8-c12b7dc1dbf3

[23] International Energy Agency, ‘World Energy Investment 2022’, International Energy Agency, Paris, 2022. Accessed: Jan. 16, 2023. [Online]. Available: https://iea.blob.core.windows.net/assets/b0beda65-8a1d-46ae-87a2-f95947ec2714/WorldEnergyInvestment2022.pdf

[24] ‘Indonesia - Measures Relating to Raw Materials (DS592). Request for the establishment of a panel by the European Union’.

[25] N. Harsono and S. Afonso, ‘Indonesia Bans Bauxite Exports in Latest Protectionist Move’, *Bloomberg.com*, Dec. 21, 2022. Accessed: Jan. 16, 2023. [Online]. Available: https://www.bloomberg.com/news/articles/2022-12-21/indonesia-bans-bauxite-exports-in-latest-protectionist-move

[26] J. P. Casey, ‘Expansion and independence: Australia’s latest rare earth mines’, *Mining Technology*, Nov. 22, 2022. https://www.mining-technology.com/features/australia-rare-earth-mines/ (accessed Jan. 16, 2023).

[27] Institute for Rare Earths and Metals, ‘Current rare earth projects’, *Institut für Seltene Erden und strategische Metalle e.V.*, Aug. 01, 2019. https://en.institut-seltene-erden.de/aktuelle-seltenen-erden-projekte/ (accessed Jan. 16, 2023).

[28] L. Gregoir and K. van Acker, ‘Metals for Clean Energy: Pathways to solving Europe’s raw materials challenge’, KU Leuven, Leuven, 2022.

[29] S. Fleming, ‘Sweden discovers biggest rare earths deposit in EU’, *Financial Times*, 2023. Accessed: Jan. 13, 2023. [Online]. Available: https://www.ft.com/content/78706a10-7ea6-445e-835c-ad8dd51b6a34

[30] Nikkei staff writers, ‘Japan to begin extracting rare earth metals from seabed in 2024’, *Nikkei Asia*, 2022. Accessed: Jan. 10, 2023. [Online]. Available: https://asia.nikkei.com/Business/Markets/Commodities/Japan-to-begin-extracting-rare-earth-metals-from-seabed-in-2024

[31] S. Okinaga, ‘Hitachi Metals developing EV motors with less China rare earths’, *Nikkei Asia*, 2022. Accessed: Jan. 10, 2023. [Online]. Available: https://asia.nikkei.com/Business/Materials/Hitachi-Metals-developing-EV-motors-with-less-China-rare-earths

[32] C. Young, ‘BMW’s Fifth-Generation Electric Motor Is a Magnet-Free Masterpiece’, Jan. 14, 2022. https://interestingengineering.com/innovation/bmws-fifth-generation-electric-motor-is-a-magnet-free-masterpiece (accessed Jan. 17, 2023).

[33] T. Vahle *et al.*, ‘Critical raw materials for the energy transition in the EU: How circular economy approaches can increase supply security for critical raw materials’, Springer International Publishing, Jan. 2022. doi: 10.1007/978-3-030-05843-2_11.

[34] J. Stibbs and S. Pan, ‘Synthetic versus natural graphite debate rages on: 2023 preview’, *Fastmarkets*, Jan. 17, 2023. https://www.fastmarkets.com/insights/synthetic-versus-natural-graphite-debate (accessed Jan. 17, 2023).

[35] B. van Wyk, ‘Is the silicon used in solar panels about to get much cheaper?’, *The China Project*, Oct. 12, 2022. https://thechinaproject.com/2022/10/12/is-the-silicon-used-in-solar-panels-about-to-get-much-cheaper/ (accessed Jan. 17, 2023).

[36] R. Long, ‘Graphite: The waning of Chinese dominance’, *Proactiveinvestors NA*, Aug. 16, 2022. https://www.proactiveinvestors.com/companies/news/990233/graphite-the-waning-of-chinese-dominance-990233.html (accessed Jan. 16, 2023).

[37] P. Harper and J. Mann, ‘Syrah Resources Ltd: graphite goes up a gear’, *Africa Outlook Magazine*, Jul. 24, 2022. https://www.africaoutlookmag.com/compan

y-profiles/1500-syrah-resources-ltd (accessed Jan. 16, 2023).

[38] IEA, 'Infrastructure and Jobs Act: Critical Minerals permitting and information', *IEA*. https://www.iea.org/policies (accessed Jan. 17, 2023).

[39] 'BHP Buys Into Tanzania Nickel Mine After Failed Canadian Bid', *Bloomberg.com*, Jan. 10, 2022. Accessed: Jan. 17, 2023. [Online]. Available: https://www.bloomberg.com/news/articles/2022-01-10/bhp-buys-into-tanzania-nickel-project-after-failed-canadian-bid

[40] US government, *Inflation Reduction Act*. Congress, 2022. Accessed: Jan. 10, 2023. [Online]. Available: https://www.congress.gov/bill/117th-congress/house-bill/5376/text

[41] O. Serpell, 'Impacts of the Inflation Reduction Act on Rare Earth Elements', *Emerging tech*, 2022. https://kleinmanenergy.upenn.edu/news-insights/impacts-of-the-inflation-reduction-act-on-rare-earth-elements/ (accessed Jan. 10, 2023).

[42] ntergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 'ntergovernmental Forum on Mining, Minerals, Metals and Sustainable Development', *Intergovernmental Forum*. https://www.igfmining.org/ (accessed Jan. 16, 2023).

[43] Energy Resource Governance Initiative, 'Energy Resource Governance Initiative Toolkit'. https://ergi.tools/ (accessed Jan. 16, 2023).

[44] European Commission, 'Critical Raw Materials Act: securing the new gas & oil at the heart of our economy', *European Commission-Statement*. 2022. Accessed: Jan. 10, 2023. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/STATEMENT_22_5523

[45] European Commission, 'Policy and strategy for raw materials', 2021. https://single-market-economy.ec.europa.eu/sectors/raw-materials/policy-and-strategy-raw-materials_en (accessed Jan. 16, 2023).

[46] 'Minerals Security Partnership', *United States Department of State*, Jun. 14, 2022. https://www.state.gov/minerals-security-partnership/ (accessed Jan. 16, 2023).

Author information

[1] **Karla Cervantes Barron** (University of Cambridge, Climate Compatible Growth): Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision.

[2] **Shobhan Dhir** (University of Oxford): Conceptualization, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing.

[3] **Jonathan M Cullen** (University of Cambridge - Climate Compatible Growth): Writing – review & editing.

**Corresponding Author:* kc512@cam.ac.uk

The brief was reviewed and edited by Simon Patterson (CCG, Loughborough University) and was designed by Sarel Greyling (Sarel Greyling Creative).

This material has been produced under the Climate Compatible Growth programme, which is funded by UK aid from the UK government, and Chatham House. However, the views expressed herein do not necessarily reflect the UK government's official policies.